

# Probing Quark-Gluon Correlations at eRHIC

eRHIC Workshop  
@ BNL, 1999

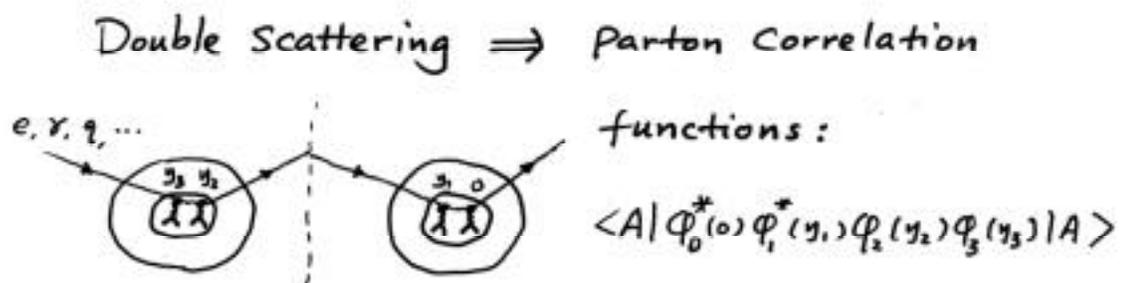
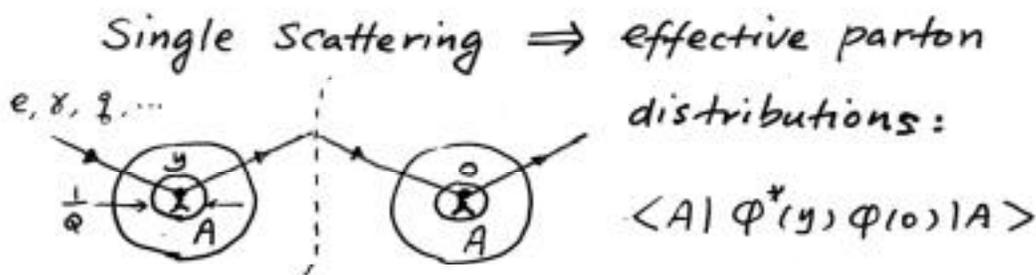
1. Why Quark-gluon Correlation functions?
2. Nuclear Dependence of Drell-Yan  $q_T$ -Spectrum  
— A successful test of Multiple Scattering in QCD.
3. Jet (or Leading hadron) transverse momentum broadening at eRHIC  
— Excellent Probe of Quark-gluon Correlation.

Based on work done with  
X. Guo, M. Luo, G. Sterman,  
X.F. Zhang.

# 1. Why Quark-gluon Correlation functions?

Quark-gluon correlation functions provide more detail and rich information on QCD dynamics than parton distributions can offer.

## \* How to measure the correlation functions?



Multiple Scattering  $\Rightarrow$  Multi-parton Correlations

But, multiple scattering is  $(\frac{1}{Q})^m$  power suppressed

## \* Need new observables:

Single Scattering's Contributions vanish or suppressed.

- \*  $A^{1/3}$ -type nuclear dependence is such an observable
  - Single hard scattering is Localized
  - Only scattering between nucleons are sensitive to the  $A^{1/3}$ -type dependence.

Examples:

- $A$ -dependence of  $q_T$ -spectrum



Small  $q_T$  kicks  
on a steeply falling  
distribution  
 $\Rightarrow$  a big effect.

- Broadening of transverse momentum square

$$\Delta \langle q_T^2 \rangle^{hA} \equiv \langle q_T^2 \rangle^{hA} - \langle q_T \rangle^{hN}$$

- ...

- \* Only small number of multiparton correlation functions are relevant to  $A^{1/3}$ -type nuclear dependence.

## 2. Nuclear Dependence of Drell-Yan $q_T$ -Spectrum.

[See Figures ④-a, b, c]

(Guo, Qiu, Zhang, hep-ph/9911476)

\* Nuclear dependence coefficient  $\alpha(A, q_T)$ :

$$\frac{d\sigma^{hA}}{dQ^2 dq_T^2} \equiv A^{\alpha(A, q_T)} \cdot \frac{d\sigma^{hN}}{dQ^2 dq_T^2}$$

\* Small  $q_T$ -region ( $\lesssim q_T^L \sim 2 \text{ GeV}$ ):

$$\alpha(A, q_T) = 1 + \frac{1}{\log A} \left[ \log(R_{DY}^A(Q^2)) + \log\left(\frac{1}{1+\chi_{DY}}\right) + \frac{\chi_{DY}}{1+\chi_{DY}} \cdot \frac{q_T^2}{\langle q_T^2 \rangle^{hN} - \Gamma(q_T^L)^{hN}} \right]$$

•  $R_{DY}^A(Q^2) \equiv \frac{d\sigma^{hA}}{dQ^2} / \frac{d\sigma^{hN}}{dQ^2}$  measurable/calculable.

•  $\langle q_T^2 \rangle^{hN} \equiv \int dq_T^2 q_T^2 \left( \frac{d\sigma^{hN}}{dQ^2 dq_T^2} \right) / \frac{d\sigma^{hN}}{dQ^2}$  measurable.

•  $\Gamma(q_T^L)^{hN} \equiv \int_{q_T^L} dq_T^2 q_T^2 \left[ \frac{d\sigma^{hN}}{dQ^2 dq_T^2} - \frac{d\sigma^{hN}}{dQ^2} \frac{1}{\langle q_T^2 \rangle^{hN}} \right] e^{-\frac{q_T^2}{\langle q_T^2 \rangle^{hN}}}$  calculable.

•  $\chi_{DY} \equiv \frac{\Delta \langle q_T^2 \rangle^{hA} - \Delta \Gamma(q_T^L)^{hA}}{\langle q_T^2 \rangle^{hN} - \Gamma(q_T^L)^{hN}} \approx \frac{\Delta \langle q_T^2 \rangle^{hA}}{\langle q_T^2 \rangle^{hN}}$  measurable/calculable.

$\alpha(A, q_T)$  given by either measurable or calculable quantities!

Leading behavior at fixed target energy:

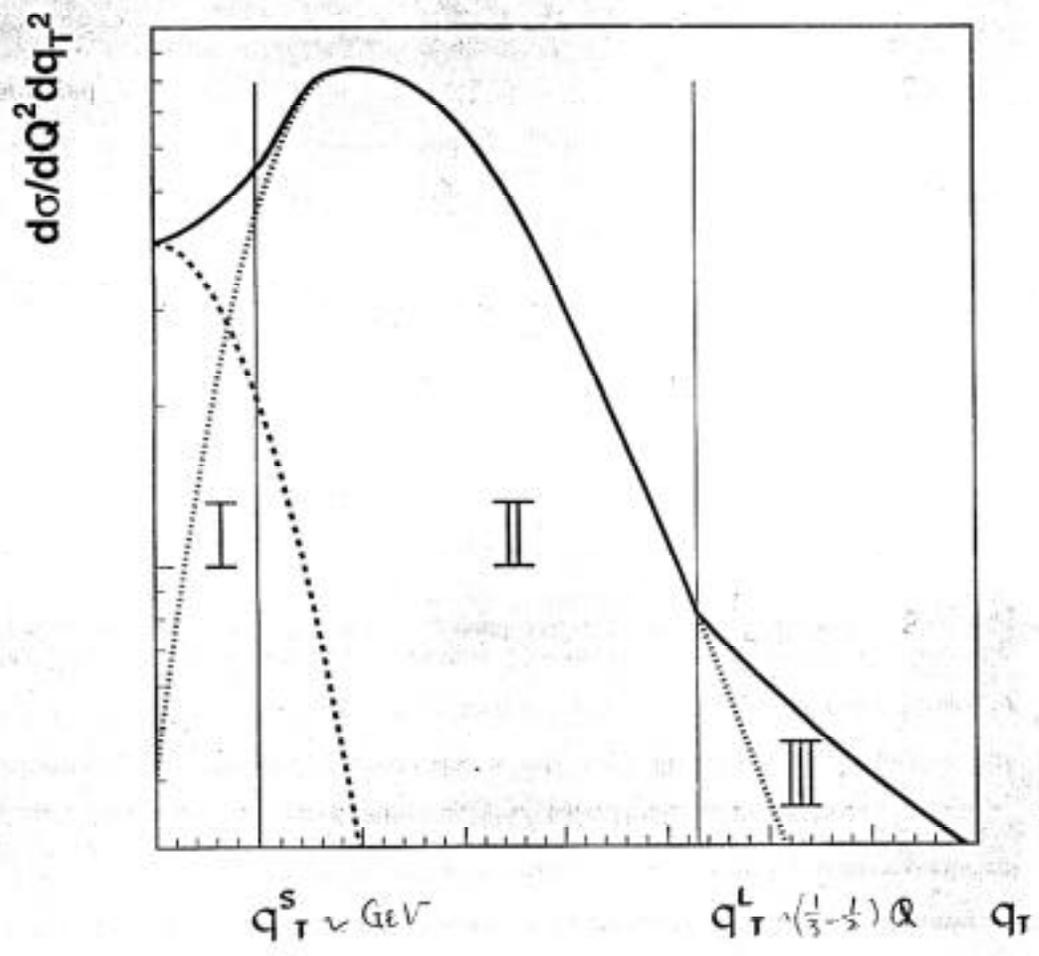
$$\alpha(A, q_T) \approx 1 + \frac{b_{DY}}{\langle q_T^2 \rangle^{hN}} \left[ -1 + \frac{q_T^2}{\langle q_T^2 \rangle} \right]$$

$$b_{DY} \equiv \frac{\Delta \langle q_T^2 \rangle^{hA}}{A^{1/3}}$$

• quadratic dependence on  $q_T^2$

• insensitive in the  $A$ .

# Drell-Yan transverse Momentum Spectrum



- (I): Intrinsic transverse Momentum  
 — Non-perturbative Fig. 1 (fix by the moments)
- (II): Resummation of large logarithms,  $(\alpha_s \ln^2(Q/q_T^S))$   
 — perturbative
- (III): Conventional fixed order perturbative calculation.

Drell-Yan transverse-momentum spectrum ④-6

Gaussian-like fit (small  $q_T$ ) + Conventional perturbative calculation.

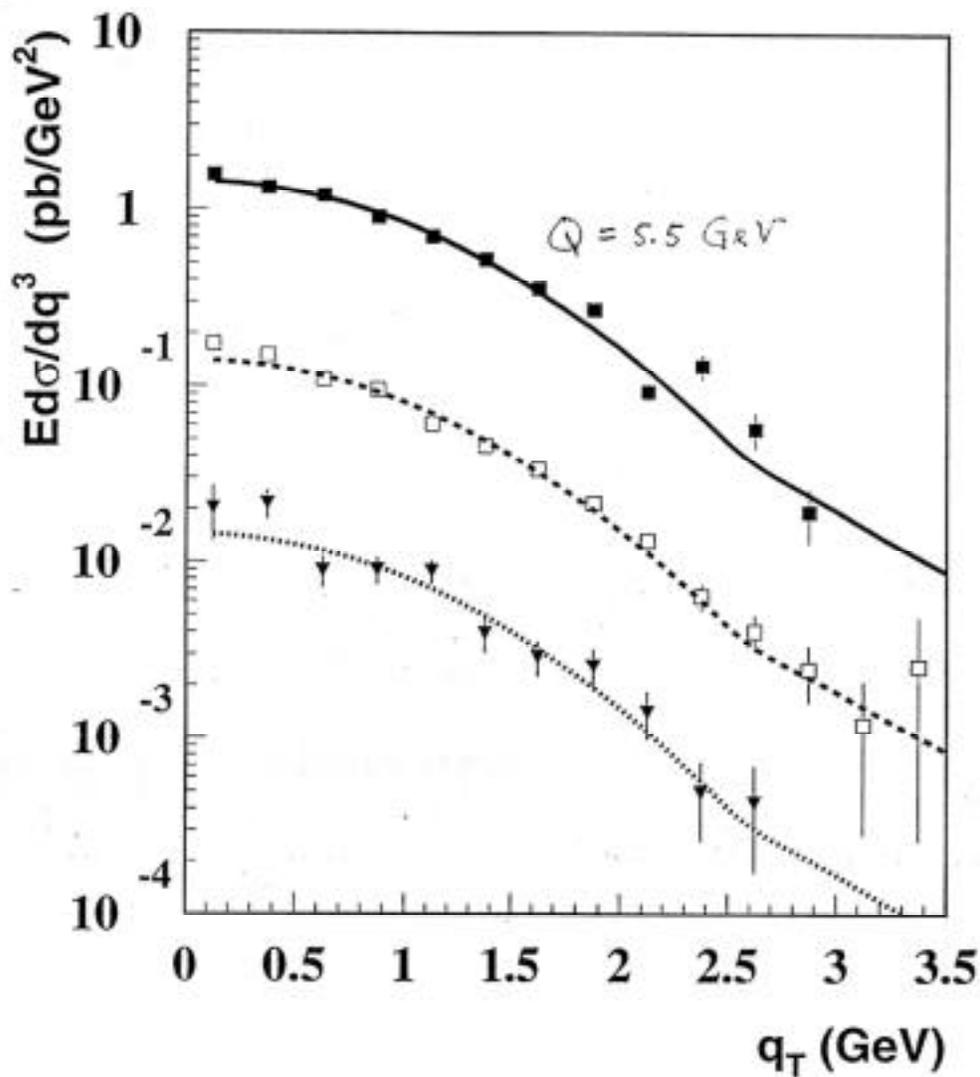
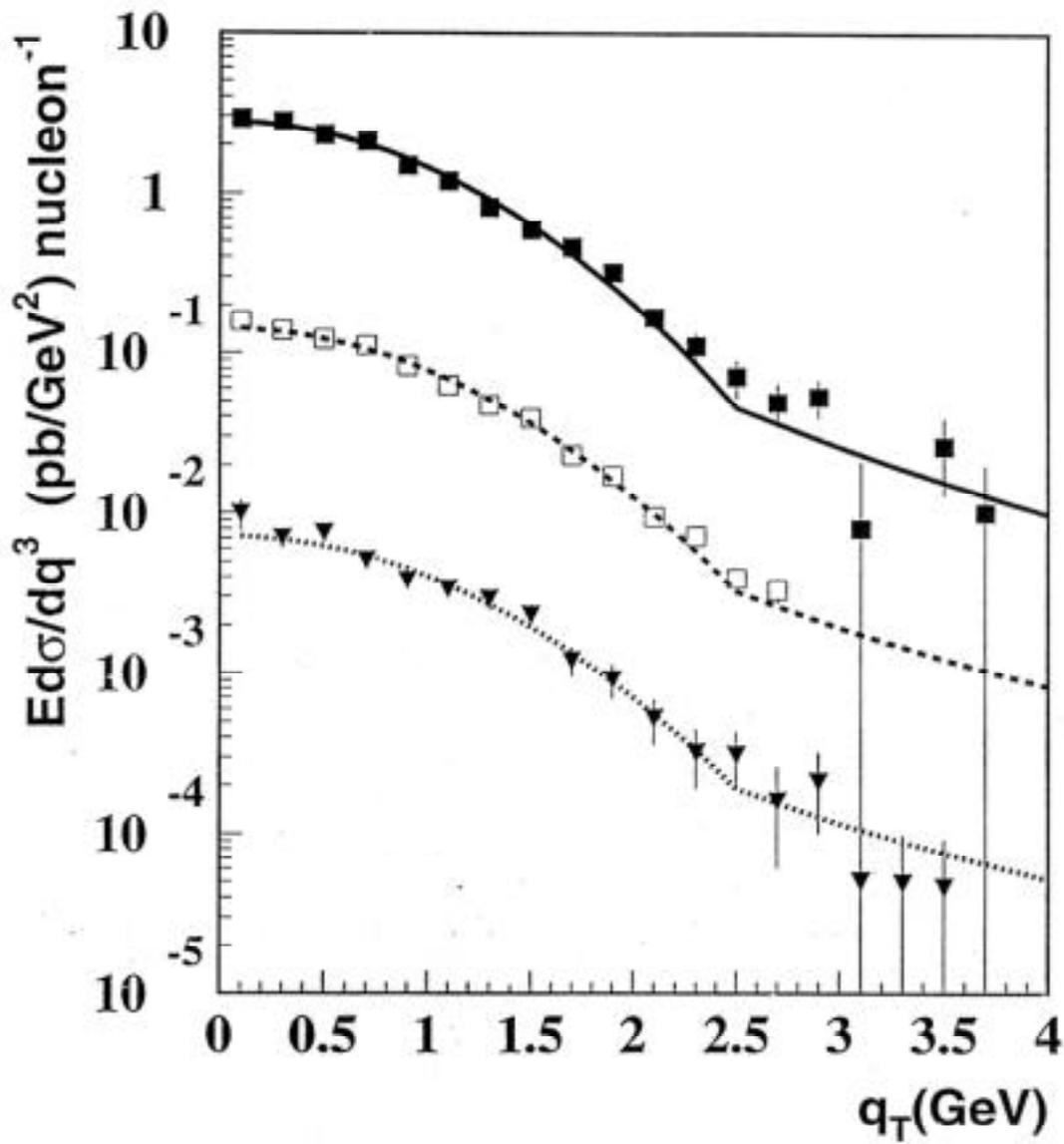


Fig.2 (a)

Drell-Yan  $q_T$ -Spectrum.



PP DATA

Fig.2 (b)

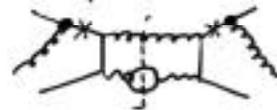
\* Large  $q_T$ -region ( $q_T > q_T^L$ ): (X. Guo, PRD 98)

$\alpha(A, q_T)$  is perturbatively calculable!

If  $q_T^L \sim O(Q)$ ,  $\alpha(A, q_T)$  depend on two types correlation functions.

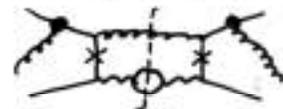
$$T_{qg}^{SH}(x) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle P_A | \bar{\Psi}_q(0) \gamma^+ \Psi_q(y^-) \\ * \int \frac{dy_1^- dy_2^-}{2\pi} \theta(y^- - y_1^-) \theta(y_2^-) \underbrace{F_\alpha^+(y_2^-) F_\alpha^+(y_1^-)}_{\text{Color force}} | P_A \rangle$$

corresponds to Soft-Hard Scattering:



$$T_{qg}^{DH}(x_A, x_B) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \frac{1}{x_B P^+} \int \frac{dy_1^-}{2\pi} e^{ix_B P^+ y_1^-} \langle P_A | \bar{\Psi}_q(0) \gamma^+ \Psi_q(y_1^-) \\ * \int dy_2^- \theta(y^- - y_1^- - y_2^-) \theta(-y_2^-) F_\alpha^+(y_2^-) F_\alpha^+(y_2^- + y_1^-) | P_A \rangle$$

corresponds to Double-Hard Scattering:



$$T_{qg}^{SH}(x) = \int dx_b T_{qg}^{DH}(x, x_b) x_b \delta(x_b) \approx \lambda^2 A q(x) \\ \text{(Luo, Qiu, Sterman)}$$

Note: Same  $T_{qg}^{SH}(x)$  determines  $\Delta \langle q_T^2 \rangle^{hA}$  or  $b_{DY}$ .

- Data on  $\Delta \langle q_T^2 \rangle^{hA}$  fix  $\lambda^2$  so as  $T_{qg}^{SH}$ ,  $T_{qg}^{DH}$ .
- $\alpha(A, q_T)$  in Large  $q_T$ -region has No free parameter.
- For  $Q \approx 5 \text{ GeV}$ ,  $\alpha(A, q_T)$  is Naturally Linked between Small  $q_T$  formula and Large  $q_T$  formula. (Figure)
- Consistent with E772 Data on  $R(A, q_T) = A^{\alpha(A, q_T)}$  (Figure)

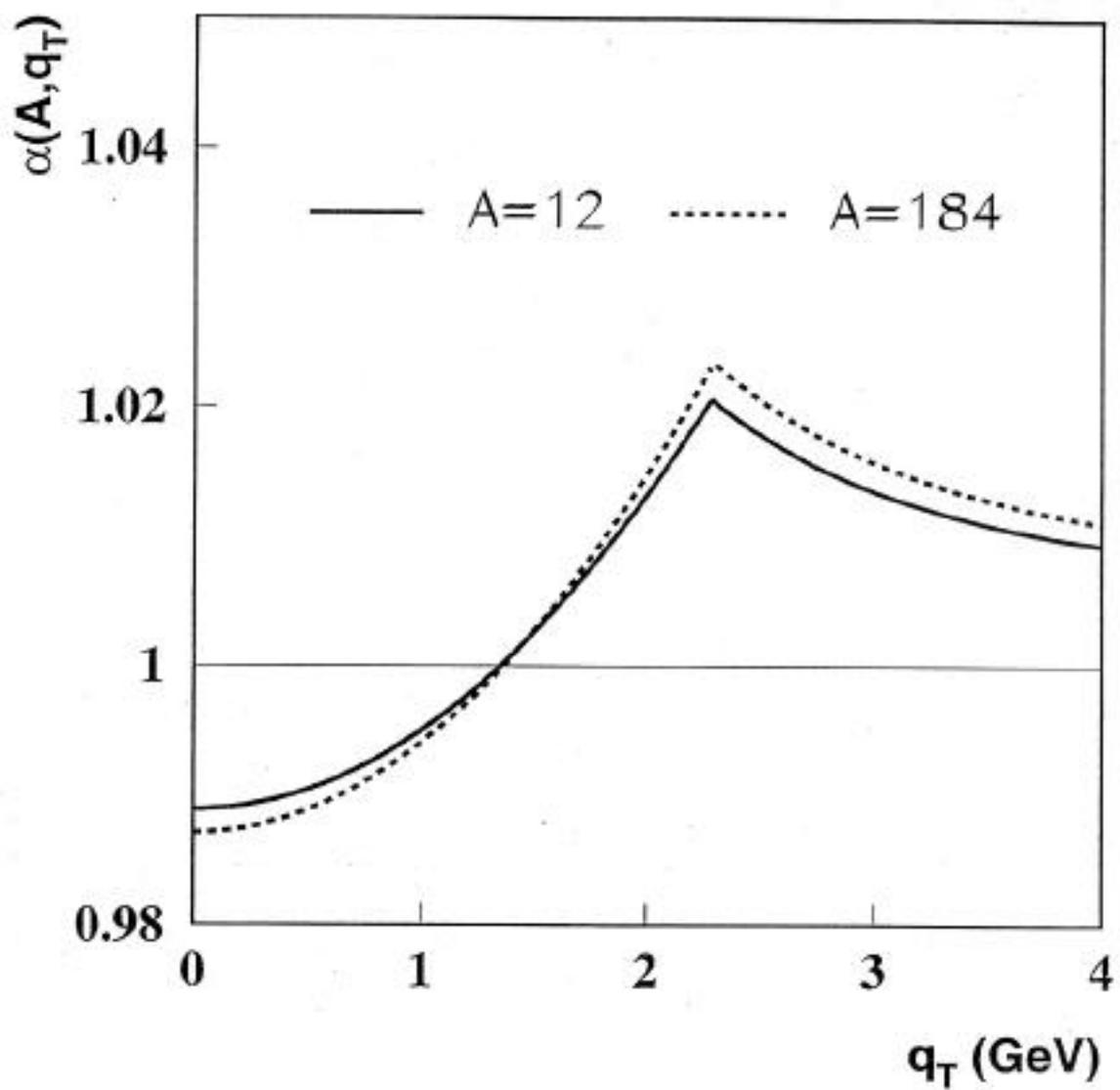


Fig.3 (a)

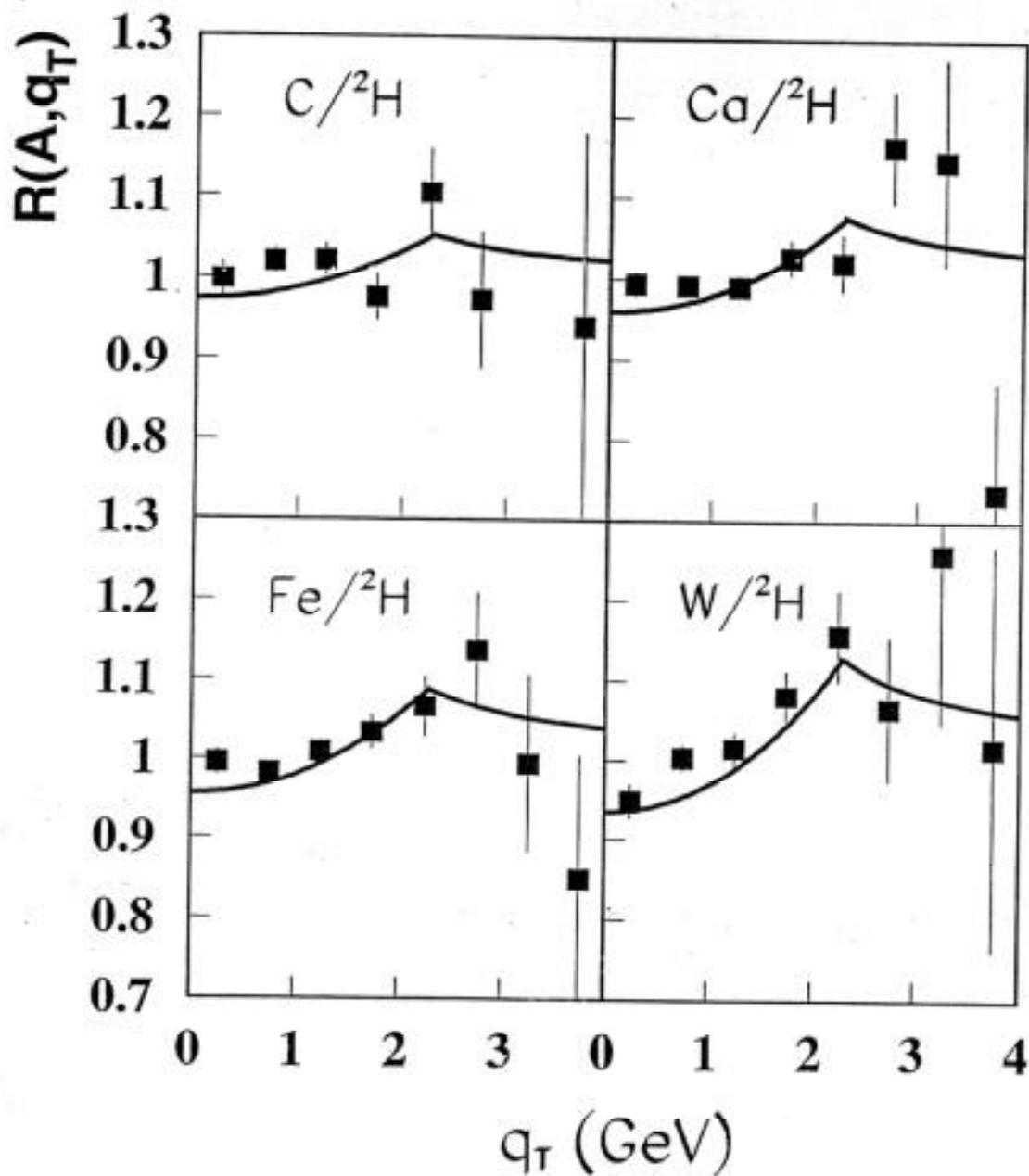


Fig.6 *E772 data on Drell-Y $\gamma$*   
*Nuclear dependence.*

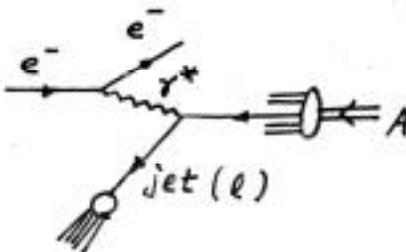
$$R(A, q_T) = A^{\alpha(A, q_T)}$$

### 3. Jet (or Leading hadron) transverse Momentum broadening at eRHIC

\* Process:  $e^- + A \rightarrow \text{Jet}(\ell) + \gamma^* + e^-$

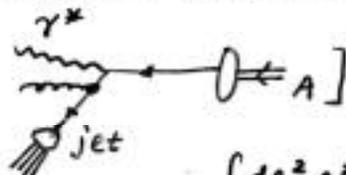
\* At leading order:

in Lab frame:



in  $\gamma^* - PA$  frame: jet transverse momentum  $\ell_T = 0$

\* High order subprocesses (radiation)



$\Rightarrow$  averaged transverse

jet momentum square

$$\langle \ell_T^2 \rangle^{eA} \equiv \frac{\int d\ell_T^2 \ell_T^2 \left( \frac{d\sigma^{eA}}{dx_B dQ^2 d\ell_T^2} \right)}{\frac{d\sigma^{eA}}{dx_B dQ^2}} \neq 0$$

\* Multiple scattering of the parton before forming the jet.



$$\Rightarrow \langle \ell_T^2 \rangle^{eA} = a + bA^{1/3}$$

*Multiple Scattering*  
No large A-dep. if  $x_B$  is Not too small.

\* Jet broadening in DIS:

$$\Delta \langle \ell_T^2 \rangle^{eA} \equiv \langle \ell_T^2 \rangle^{eA} - \langle \ell_T^2 \rangle^{eN} \approx \frac{\int d\ell_T^2 \ell_T^2 \left( \frac{d\sigma_{\text{Double}}^{eA}}{dx_B dQ^2 d\ell_T^2} \right)}{\frac{d\sigma^{eA}}{dx_B dQ^2}} \approx \underbrace{\hspace{10em}}_{\text{calculable!}} = bA^{1/2}$$

\* QCD Prediction for Jet broadening: (x. Guo, PRD 99)

Same technique used to calculate  $\Delta \langle q_T^2 \rangle^{hA}$  for Drell-Yan process leads to

$$\Delta \langle q_T^2 \rangle^{eA} = \left( \frac{4\pi\alpha_s}{3} \right) \frac{\sum_q e_q^2 T_{q/A}^{SH}(x_B)}{\sum_q e_q^2 q_A(x_B)}$$

- No extra free parameter! (Same  $T_{q/A}^{SH}(x_B)$  from DY case)
- Measurement of  $\Delta \langle q_T^2 \rangle^{eA}$  as a function of  $x_B, Q^2$   
 $\Rightarrow$  direct measurement of the quark-gluon  
 Correlation function  $T_{q/A}^{SH}(x_B)$
- Excellent process to test the model:  $T_{qq}^{SH}(x_B) = \lambda^2 A^{1/3} q_A(x_B)$

Within this model,

$$\Delta \langle q_T^2 \rangle^{eA} = \left( \frac{4\pi\alpha_s}{3} \right) \lambda^2 A^{1/3} = \Delta \langle q_T^2 \rangle_{DY}^{hA}$$

- independent of  $x_B$
- Small  $Q^2$ -dependence.
- Same as  $\Delta \langle q_T^2 \rangle_{DY}^{hA}$ .
- Value of  $\lambda^2 \sim F^2$  (Color force)

Formula is valid for Non-saturation region.

If we push it to saturation,  $F^2 \sim \frac{1}{g^2}$

$$\Rightarrow \Delta \langle q_T^2 \rangle = \text{const} \cdot A^{1/3}$$



## 4. Summary

- \* Quark-gluon correlation functions as fundamental as parton distributions.
- \* QCD factorization provides systematic way to calculate physical observables sensitive to these correlation functions.
- \*  $A^{1/3}$ -type nuclear dependence is a good observable to extract information on parton correlation between nucleons, which are valuable for studying RHIC physics.
- \* Nuclear dependence of Drell-Yan  $g_T$ -spectrum demonstrates that QCD calculations are not only consistent for different observables, but also testable with better data.
- \* Jet broadening at eRHIC provides a direct and critical test of the QCD approach.